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Break-Monsoon Over India

K. RAGHAVAN—*Indian Institute of Tropical Meteorology, Poona, India*

ABSTRACT—Interruption of monsoon rainfall by prolonged spells of sparse rainfall (break-monsoon) during the mid-monsoon months of July and August over the plains of northern India (20°–29°N, 75°–85°E) has been investigated. When a tropical low-pressure system moves from the plains in a northerly direction toward the submontane region of the Himalaya, the monsoon trough of low pressure also moves from the plains to that region. This deprives the plains of northern India of significant ascending motion and normal rainfall and brings about the break-monsoon. During the break-monsoon period, descending motion takes place from the stratosphere to the lower troposphere over the plains, while ascending motion occurs in the regions to the north and south of the plains. As the descending motion persists over the plains, the break-monsoon intensifies and the weather turns mainly dry. A vertical circulation model for the break-monsoon period is proposed. The break-monsoon ceases and normal monsoon conditions are re-established when the monsoon trough returns to the plains and intensifies. This occurs in association with tropical low-pressure systems developing at or near the Bay of Bengal and moving toward the plains. The genesis and persistence of the break-monsoon, therefore, depends mainly on the interaction between the monsoon trough and tropical low-pressure systems of the Indian region.

1. INTRODUCTION

July and August, the principal monsoon months in India, account for nearly 75 percent of the annual rainfall over a major part of the country. During these 2 mo, it rains almost daily; this is, perhaps, an important distinguishing feature of monsoonal weather. In certain years, the monsoonal weather in some regions is interrupted by long periods of sparse rainfall called *break-monsoons*. This unseasonal weather is disastrous for crops, and it is responsible for severe droughts and famines. A break-monsoon over an extensive area is considered a national calamity since it has a serious detrimental effect on the economy of the country.

According to Pisharoty and Asnani (1960), the break-monsoon is caused by eastward extension of the subtropical anticyclone at 500 mb over the Sahara Desert and Arabia into central India where the ridge inhibits ascending motion. While corroborating this, Ramaswamy (1962) has attempted to explain how the subtropical anticyclone extends as a ridge to central India in the rear of extratropical westerly waves.

According to Dixit and Jones (1965), the break-monsoon is the result of westward extension of the Pacific subtropical anticyclone across the Central Bay of Bengal into central India at 500 mb and above.

These studies all contain the same serious defect: the authors arrived at their conclusions by comparing and contrasting periods of active monsoon with break-monsoon. Extension of the subtropical ridge from the west or east, or any other circulation change observed after the onset of break-monsoon, need not necessarily be a causative factor of the break-monsoon; it may actually be an effect of break-monsoon. A more rational approach to this problem, therefore, is to study the sequence of important circulation changes that lead to break-monsoon. For this purpose, only changes in the circulation responsible for the normal rainfall are to be considered important. If, in this manner, we learn the basic cause of the break-monsoon, we may be able to determine how the break-monsoon is maintained and what circulation changes follow from it. Results of such an investigation for the plains of northern India (20°–29°N, 75°–85°E) are discussed here. Forty observation stations provide regular rainfall reports in this region. A break-monsoon begins on the day when at least 75 percent of these stations record rainfall 50 percent or more below normal.

2. RAINFALL IN THE PLAINS OF NORTHERN INDIA

During the monsoon season, the most conspicuous feature of the circulation over India is the trough of low pressure in the lower and middle tropospheric westerlies. This trough is fully developed by July and remains so in August. In the mean, the axis of the trough at sea level runs west-northwest to east-southeast, almost parallel to and about 300 km south of the Himalaya (Normand 1943). Nearly two-thirds of the plains are situated south of the sea-level trough axis.

On the average, rainfall is minimal at the latitude of the sea-level trough axis (Blanford 1886). Figure 1 shows the normal distribution of rainfall and rainy days along 80°E, which runs through the center of the plains. At 80°E, the sea-level trough axis is at about 26°N. North of the sea-level trough axis, the rainfall and rainy days increase toward the Himalaya. Figure 2 shows that the terrain in this area increases in height toward the Himalaya, which has an average elevation of over 5 km. Here, the low-level winds normally have a southerly component directed against the slope, and the rainfall and number of rainy days generally increase with altitude. Apparently, rainfall in this area is controlled primarily by orography.

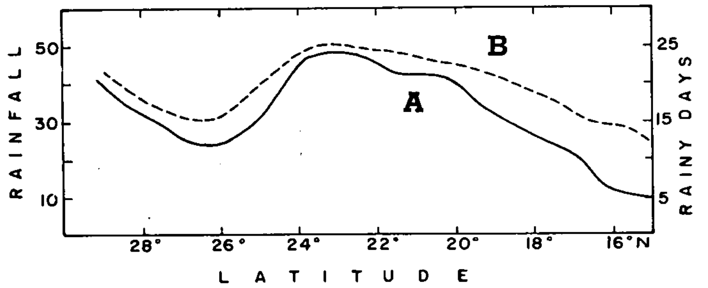

FIGURE 1.—(A) normal rainfall (cm) and (B) number of rainy days (days with 0.3 mm or more rainfall) along 80°E during July.

TABLE 1.—*Normal winds in July at 0.6 km above sea level*

Station	Direction (deg.)	Speed (kt)
Malegaon (20°33′N, 74°32′E)	261	15
Nagpur (21°06′N, 79°03′E)	273	11
Raipur (21°14′N, 81°39′E)	258	15
Jabalpur (23°10′N, 79°57′E)	254	11

The rainfall increases south of the sea-level trough axis also. A major part of the plains between 20° and 26°N is, therefore, an area of relatively heavy rainfall with maximum rainfall occurring near 23°N. Between 20° and 26°N, there is a hilly plateau oriented roughly west-southwest to east-northeast (255°–75°) with an average elevation of 500 m. Since this plateau is situated within the zone of heavy rainfall, one may be tempted to believe that its orographic features are mainly responsible for the rainfall. Examination of the normal winds over this area does not support this assumption, however, since the normal seasonal winds do not blow against the plateau but nearly parallel to it (table 1).

It is curious that, despite the absence of significant orographic influence, it rains over this area almost every day (20–25 days/mo), totaling about 40 cm/mo. The high incidence of precipitation suggests the existence of some seasonal synoptic feature capable of producing rising motion almost persistently. We know from the normal circulation (Raman and Dixit 1964, Frost and Stephenson 1965) that the monsoon trough over this area extends upward to at least the middle troposphere (fig. 3). The trough slopes southward with height; therefore, at about 500 mb, its axis is at the southern boundary of the plains near 20°N. Apparently, this seasonal trough and its associated upward motion are mainly responsible for the typical monsoon rainfall in the area.

In the extratropical regions, the maximum precipitable water vapor is usually found near 700 mb. A recent study by Banerji et al. (1967) suggests that this is true for the monsoon region also. At 700 mb, the monsoon trough axis in the plains runs roughly along 23°N, where the rainfall is maximum. This level of the atmosphere, where the water vapor is normally high, probably takes maximum advantage of the trough axis and its associated upward motion and contributes to greater amounts of rainfall around 23°N.

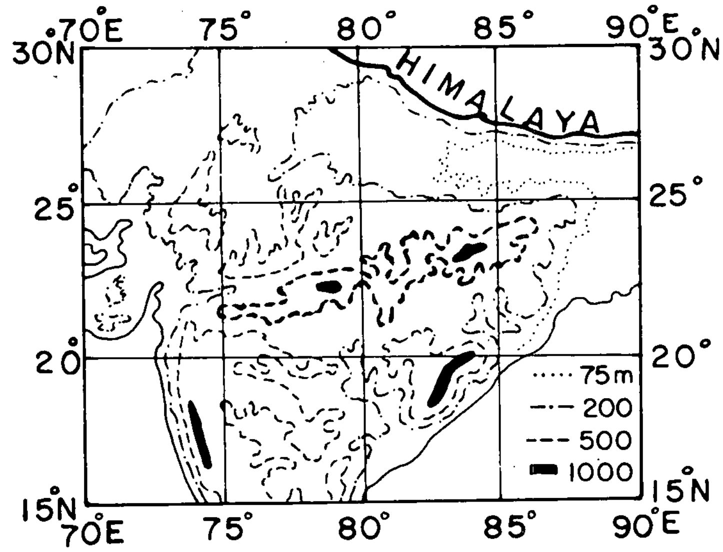

FIGURE 2.—Topography of the region of interest.

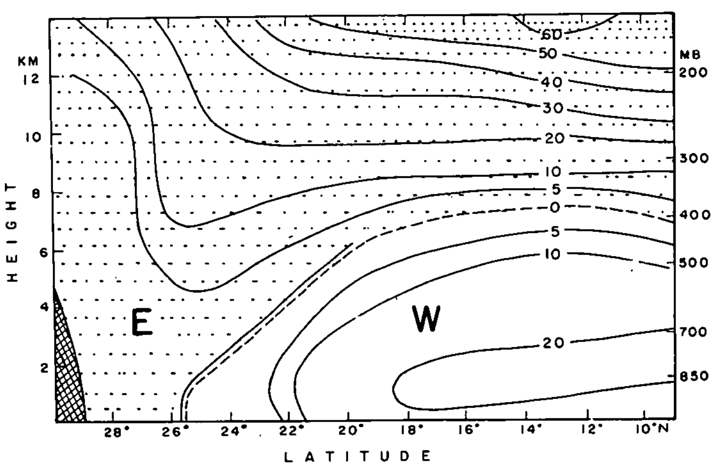

FIGURE 3.—Mean zonal wind component (kt) in July along 80°E. The monsoon trough axis is indicated by the parallel solid and dashed lines. The dotted portion indicates easterlies.

It may be relevant to point out here that the western end of the monsoon trough, which reaches North Africa where it is usually called the intertropical convergence zone, also slopes southward with height. Thompson (1965) has shown that, on the average, heavy rainfall occurs near the region where the 700-mb trough axis prevails.

These aspects of rainfall lead us to believe that, if the monsoon trough loses its normal southward slope and remains vertical, there would be no zone of heavy rainfall along 23°N. In other words, there would be a general decrease of rainfall south of the sea-level trough axis. In the immediate vicinity of the sea-level trough axis, however, no decrease of rainfall would be expected. On the contrary, an increase of rainfall is possible because the trough over the area is vertical over a depth of about 500 mb. During a severe break-monsoon, however, the plains as a whole suffer from below-normal rainfall. It follows, therefore, that during the break-monsoon, the monsoon trough should not be present in the plains at all; it should migrate away from the plains.

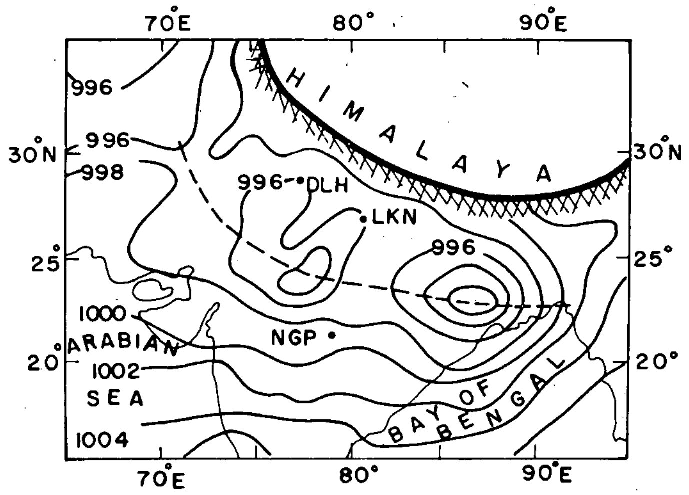

FIGURE 4.—Sea-level isobars (mb) for 0300 GMT, July 28, 1965. The dashed line is the trough axis.

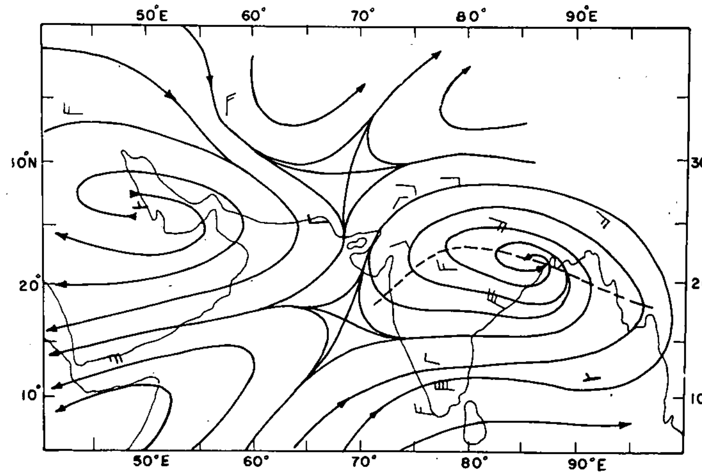

FIGURE 5.—Winds at 500 mb for 0000 GMT, July 28, 1965.

If the trough migrates from the plains to a position south of 20°N, the rainfall over the 300-km belt of the plains adjoining the Himalaya may not significantly decrease since the direction of the low-level winds may still be favorable for orographic rainfall. On the other hand, if the trough migrates beyond the northern boundary of the plains, the winds over the area would be mainly westerly, unfavorable for local orographic rainfall.

It seems reasonable, therefore, that the monsoon trough must migrate north of the plains without its usual southward slope to bring about a break-monsoon over the plains of northern India. This means that, during the break-monsoon, the axes of the monsoon trough at both sea level and in the upper air would lie along approximately the same latitude near the Himalaya. Examination of the records of the past half century shows that this important inference is remarkably true. Before we consider what causes the axis of the trough to migrate to the foothills of the Himalaya and how it loses its southward slope, leading to break-monsoon, we should note that for several years the operational forecasters have been considering the migration of the axis of the sea-level monsoon trough to the foothills of the Himalaya as an indication of the onset of break-monsoon over northern India. Perhaps, it is for this reason that the Indian Daily Weather Reports have been publishing the daily location of the sea-level monsoon trough axis since about 1913. From the above discussion, we are now able to understand the physical significance of the sea-level trough axis at the foothills of the Himalaya.

3. GENESIS OF BREAK-MONSOON

In light of the above considerations, a number of break-monsoons that lasted at least for 5 days, particularly those from 1951 to 1970, have been examined. We know that when a tropical disturbance (depression or Low) is present in the plains, the axis of the monsoon trough passes through the center of the disturbance. When this disturbance, which has a closed circulation up to about 700 mb, moves north or south, the monsoon trough axis at all heights over a wide longitudinal belt moves with it. In the plains, particularly north of 26°N, the disturbances have little or no southward slope in the vertical up to about 500 mb except on rare occasions for a period of about 1 day. Therefore, the monsoon trough loses its usual southward slope when there is a tropical disturbance in the plains of northern India.

Interaction between the large-scale monsoon trough and the transient small-scale monsoon disturbance is a complicated process. A quantitative measurement is necessary to assess the importance of this interaction in comparison to other terms in the energy budget during the monsoon season. Though this nonlinear interaction between the stationary and transient disturbances is only of secondary importance in extratropics (Murakami 1963, Wiin-Nielsen et al. 1964), synoptic experience shows that it is of primary importance during the Indian monsoon. The simultaneous northward movement of the small-scale disturbance and the monsoon trough (without southward slope) from the plains to the Himalaya leads to the break-monsoon condition.

For example, two tropical disturbances were observed in the Indian region in the last week of July 1965. On July 28, a depression was east of the plains at 23°N, 87°E; and a Low was over the plains at 24°N, 78°E (fig. 4), extending up to about 600 mb. The axis of the monsoon trough passed through the centers of these two disturbances. Upper wind observations were few on this day. Figure 5 indicates, however, that the monsoon trough extended up to 500 mb with little or no slope in the vertical over the plains.

Under the influence of the Low, widespread precipitation occurred in the plains with the usual heavy rainfall in the southern sector of the Low (fig. 6). There were a few heavy rainfalls in the southeastern parts of the plains also, probably due to the depression.

By August 1, the Low had moved north to 28°N, 79°E (fig. 7) accompanied by a northward shift of the monsoon trough axis at all heights (fig. 8). Heavy rainfall was observed in the vicinity of the Low (fig. 9). Normally, one would also expect significant amounts of rainfall elsewhere under the influence of the monsoon trough, but

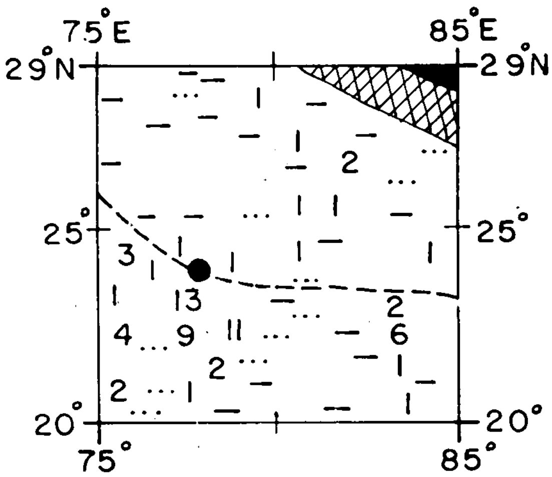

FIGURE 6.—Sea-level trough axis (dashed line) for 0300 GMT, July 28, 1965, and rainfall (cm) during the next 24 hr. A single dash represents 0.3–0.7 cm and three dots represent less than 0.3 cm. The large dot indicates the Low center.

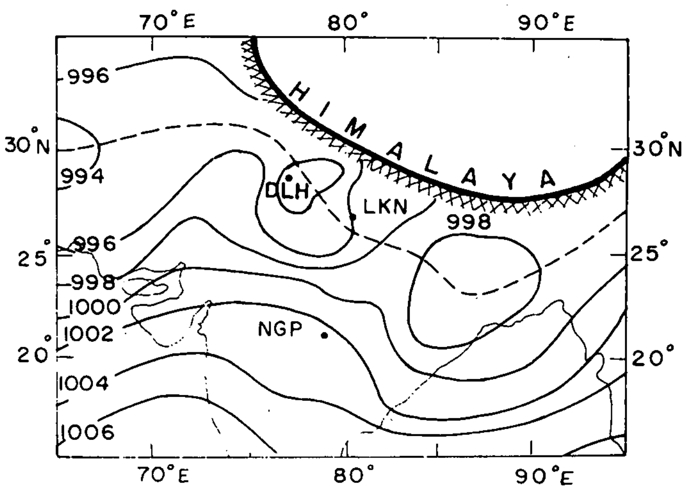

FIGURE 7.—Sea-level isobars (mb) for 0300 GMT, Aug. 1, 1965.

because the trough was nearly vertical to about 500 mb, rainfall to the south of the sea-level trough axis was negligible.

By the following day, the Low and a major portion of the sea-level monsoon trough had moved northward against the hill ranges, and westerly flow prevailed at sea level over the entire plains. During this period, the Low and the monsoon trough weakened—the Low did not extend above 700 mb, and the 500-mb flow over India became mainly westerly (fig. 10)—and a high-pressure ridge developed at sea level (fig. 11). At 700 mb (fig. 12) and 850 mb (not shown), the Low persisted close to the northern border of the plains and only at these levels did the broad easterly flow persist. The western end of the 700-mb monsoon trough passed through the center of this Low while the eastern end passed through another Low near the head of the Bay of Bengal; therefore, in the lower troposphere, the monsoon trough still prevailed over the northern parts of the plains with a small southward slope with height. Figure 13 shows the rainfall associated with this trough. In the southern parts where there was no upper air trough, the rainfall showed a general decrease.

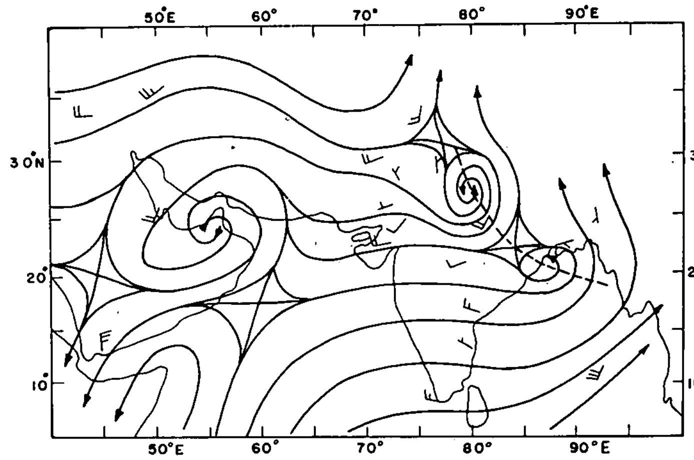

FIGURE 8.—Winds at 500 mb for 0000 GMT, Aug. 1, 1965.

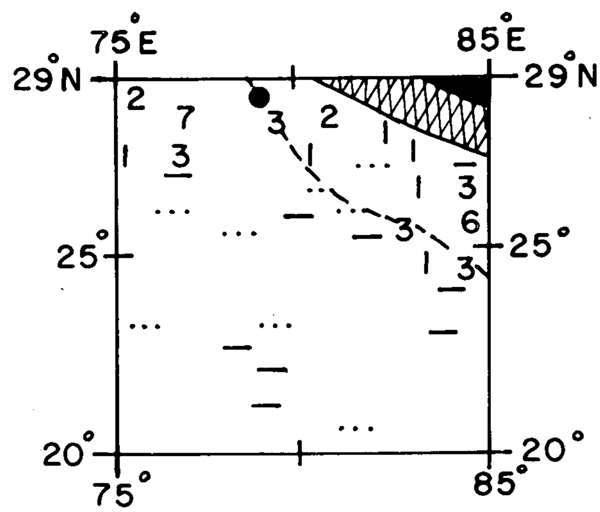

FIGURE 9.—Sea-level trough axis for 0300 GMT, Aug. 1, 1965, and rainfall (cm) during the next 24 hr.

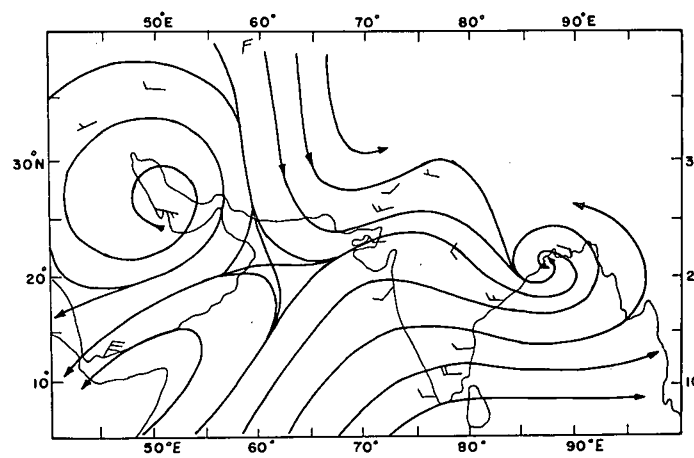

FIGURE 10.—Winds at 500 mb for 0000 GMT, Aug. 2, 1965.

By the afternoon of August 3, the lower troposphere Low and monsoon trough had both moved north to the hill ranges of the Himalaya. The Low near the head of the Bay of Bengal had weakened and became unimportant. With the shift of the monsoon trough to the foothills of the Himalaya, the winds over the plains of northern India became westerly (fig. 14), and a break-monsoon was established over the region (fig. 15).

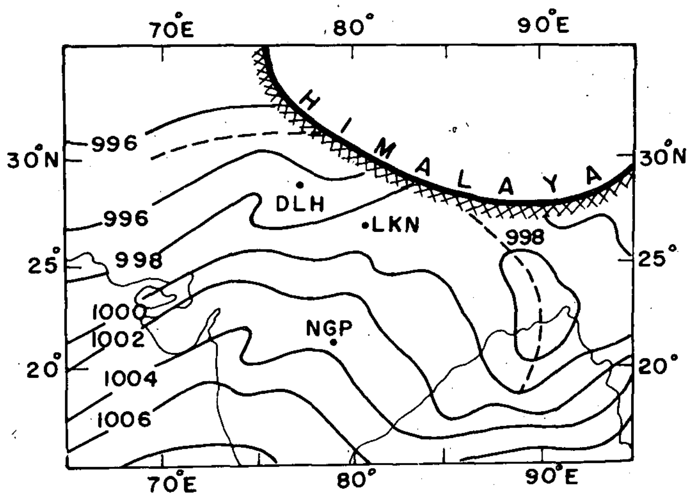

FIGURE 11.—Sea-level isobars (mb) for 0300 GMT, Aug. 2, 1965.

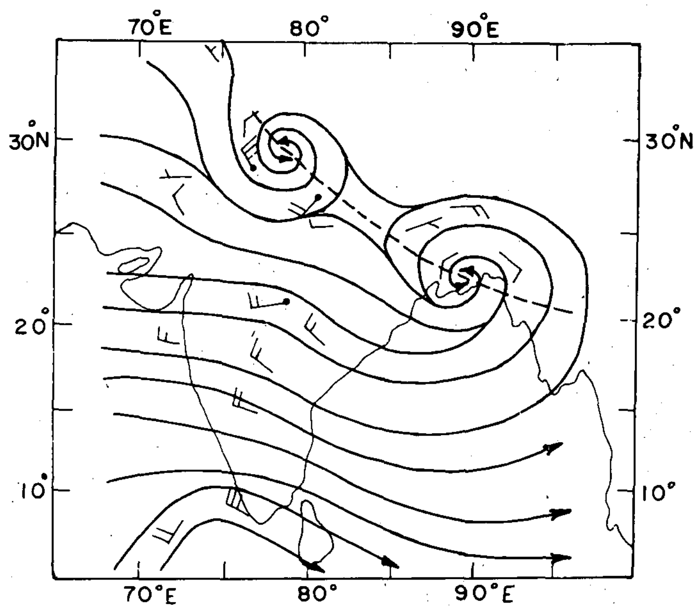

FIGURE 12.—Winds at 700 mb for 0000 GMT, Aug. 2, 1965.

It is important to note (fig. 16) that the subtropical anticyclone was in its normal position, and it did not extend eastward as a ridge over northern India. Similarly, there was no anticyclonic ridge extending over the region from the east.

4. ROLE OF UPPER AIR LOWS

Occasionally, tropical disturbances in the plains of northern India lose their circulation between sea level and 900 mb. Between 900 and 700 mb, however, the circulation persists, influences the monsoon trough, and causes a break-monsoon just as any other tropical disturbance that extends upward from sea level would. For instance, at 0300 GMT on July 16, 1963, a Low was situated over the plains at about 26°N, 80°E, with cyclonic circulation extending up to about 700 mb. By 1200 GMT, the circulation below 900 mb had disappeared, and the sea-level Low had filled. From 900 to 700 mb, however, the Low persisted. It was most pronounced at 900 mb (fig. 17).

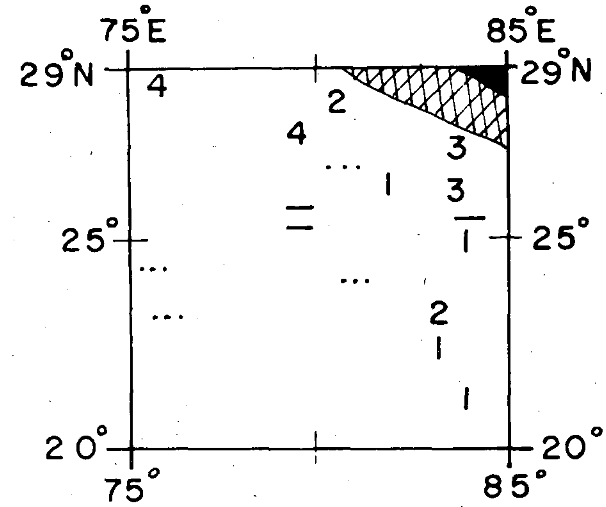

FIGURE 13.—Rainfall (cm) during the 24-hr period ending 0300 GMT, Aug. 3, 1965.

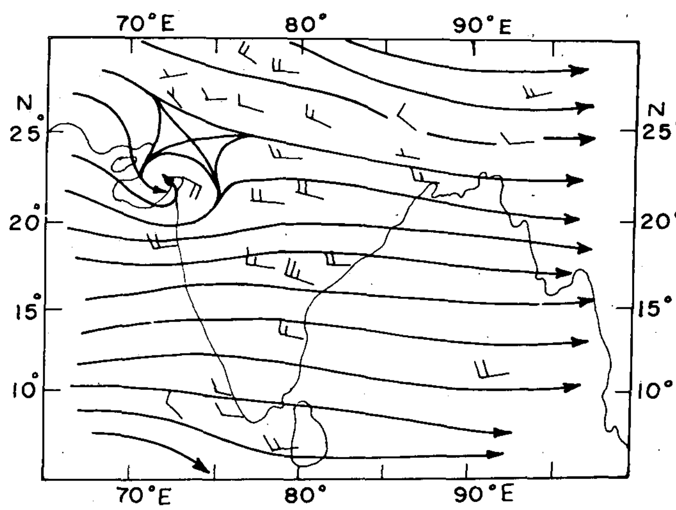

FIGURE 14.—Winds at 700 mb for 1200 GMT, Aug. 3, 1965.

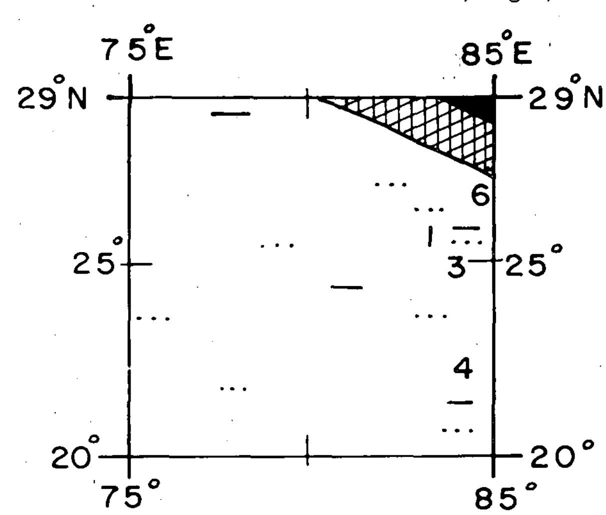

FIGURE 15.—Rainfall (cm) during the 24-hr period ending 0300 GMT, Aug. 4, 1965.

By July 19, the upper air Low and the associated upper air monsoon trough had moved north of the plains to the hill ranges (fig. 18). At sea level, however, the trough persisted near the foothills of the Himalaya. Conditions thus became favorable for the break-monsoon.

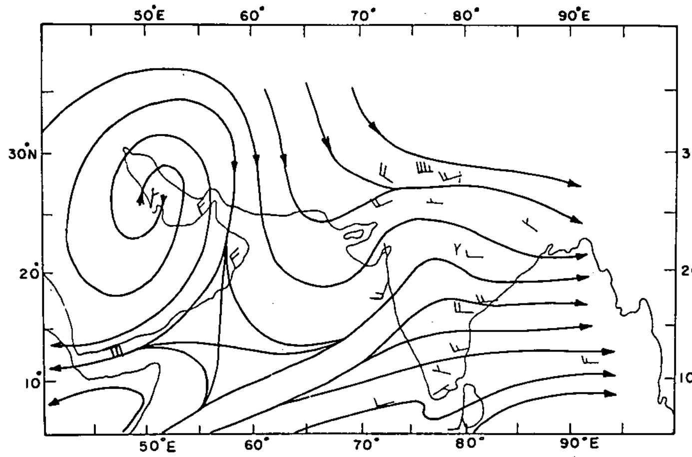

FIGURE 16.—Winds at 500 mb for 1200 GMT, Aug. 3, 1965.

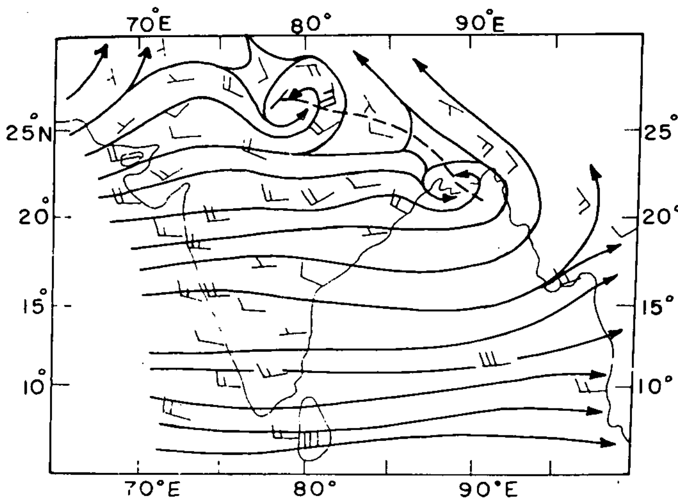

FIGURE 17.—Winds at 900 mb for 1200 GMT, July 16, 1963.

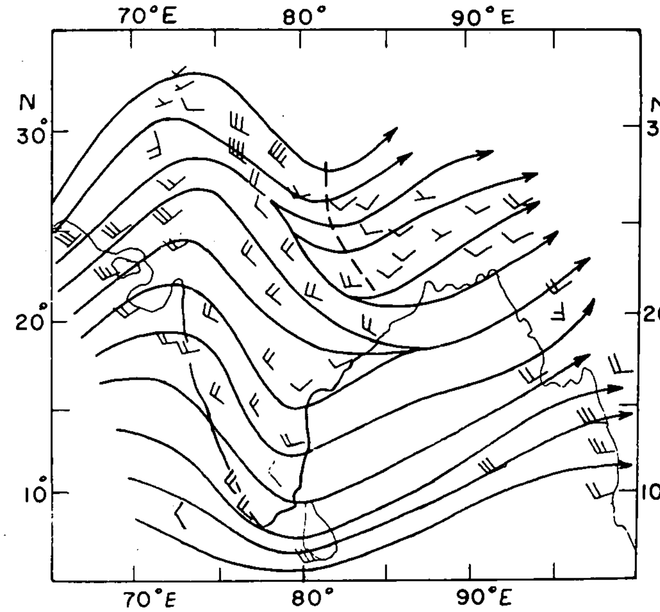

FIGURE 18.—Winds at 850 mb for 0000 GMT, July 19, 1963.

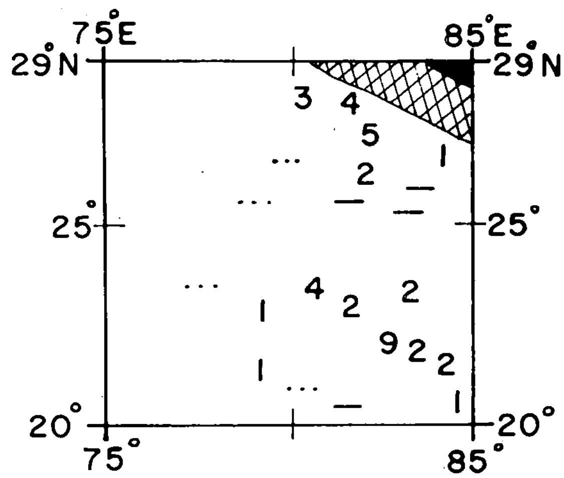

FIGURE 19.—Rainfall (cm) during the 24-hr period ending 0300 GMT, July 20, 1963.

5. INFLUENCE OF THE UPPER AIR TROUGH ON THE BREAK-MONSOON

In the previous section, we observed that the July 19, 1963, conditions were favorable for the onset of break-monsoon. Curiously enough, however, the break-monsoon did not occur on that day, as evidenced by the copious rainfall over a large area of the plains (fig. 19). Examination of the circulation on July 19 reveals a north-south trough in the lower troposphere extending from the foothills of the Himalaya onto the plains (fig. 18). This trough extended upward to about 700 mb and was apparently responsible for the rainfall and the delay in the onset of break-monsoon. By the next day, the upper air trough had moved east beyond 90°E and the break-monsoon over the plains had commenced (fig. 20).

These upper air troughs differ from the seasonal trough in that they are transient and oriented north–south. They occur at one or more levels between 900 and 700 mb, usually after the seasonal trough shifts away from the plains. Though they do not generally last more than 2 days, they cause considerable rainfall and temporarily restrain the onset of break-monsoon.

One should note that on July 19 a strong 500-mb ridge extended from Iran to the plains of northern India (fig. 21). As seen from figure 19, this ridge did not cause a break-monsoon over the plains. On the next day, when the break-monsoon set in, the ridge did not persist over the plains but moved away to the central Arabian Sea; over the plains, the winds were mainly westerly (fig. 22). This leads us to seriously doubt whether the circulation at the 500-mb level, which is normally the transitional upper periphery of the westerly monsoon current, plays any decisive role in the production of weather in the plains of northern India. From the observations presented here, the circulation in the layer of the atmosphere below 500 mb appears to control the weather. This is in accord with the recent findings of Krishnamurti and Hawkins (1970). Whether or not a ridge exists at or above 500 mb appears to have little influence on the onset of the break-monsoon in the plains. What matters most is the absence of the monsoon trough below 500 mb over the plains. There is, however, little doubt that a ridge is present at 500 mb

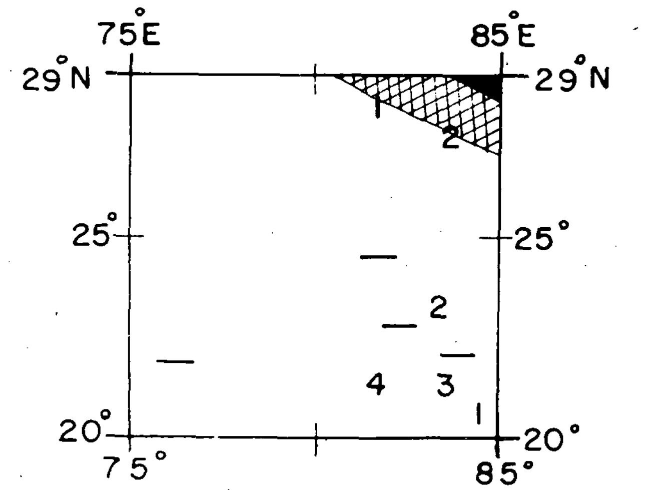

FIGURE 20.—Rainfall (cm) during the 24-hr period ending 0300 GMT, July 21, 1963.

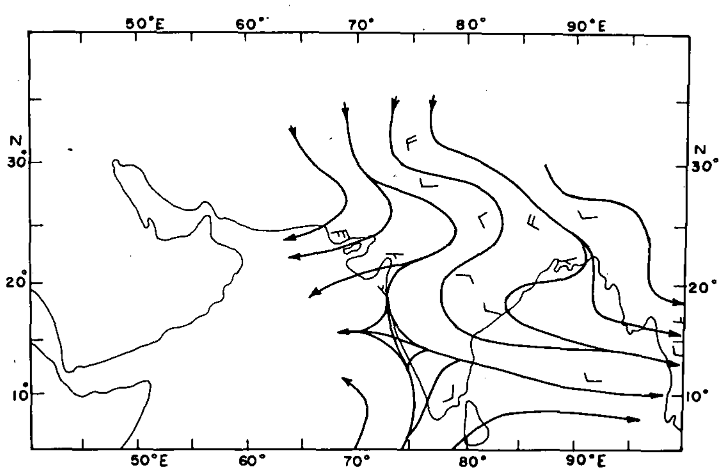

FIGURE 21.—Winds at 500 mb for 0000 GMT, July 19, 1963.

over the plains during the intense break-monsoons, as pointed out by Pisharoty and Asnani (1960) and Dixit and Jones (1965).

6. INTENSIFICATION OF BREAK-MONSOON

After the onset of break-monsoon, atmospheric conditions undergo steady changes over the plains, gradually improving to generally cloudless skies and rainless days. Figure 23 shows how the rainfall decreased day by day during the break-monsoon of August 1965 and culminated in dry weather over nearly all of the plains on August 8 and 9. During break-monsoons, the surface temperature increases rapidly to above-normal values; the mean temperature during the period approaches that in June, which is the hottest month of the monsoon season. However, the seasonal trough of low pressure persists at the foothills of the Himalaya and not over the plains where the temperature maximum is observed. Although this is an interesting aspect of the monsoon circulation over the country, we are presently interested in the changes in the atmosphere that lead to dry weather or intensification of break-monsoons.

Examination of the moisture content of the atmosphere shows no systematic decrease of moisture during break-

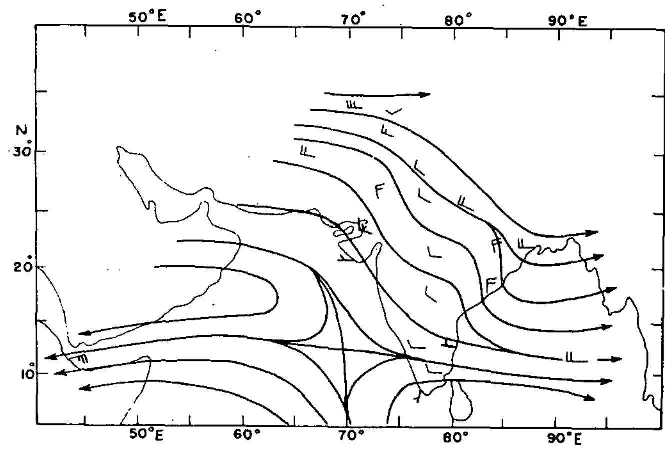

FIGURE 22.—Winds at 500 mb for 1200 GMT, July 20, 1963.

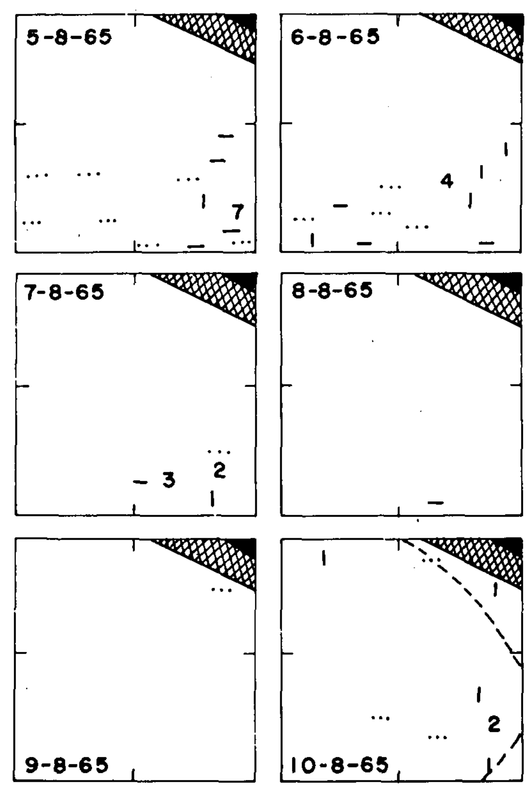

FIGURE 23.—Rainfall (cm) in the plains during the break-monsoon of August 1965.

monsoons that can account for the dry weather. In fact, the moisture content on certain days is as high as that on days of normal monsoon (fig. 24). We must, therefore, look for changes in the vertical circulation of the atmosphere.

7. VERTICAL CIRCULATION

As the monsoon trough migrates to the foothills of the Himalaya, leading to break-monsoon condition, the sea-level pressure south of the trough naturally increases. Even after the monsoon trough reaches its northernmost position close to the Himalaya, however, the sea-level pressure generally continues to increase. In 1965, for example, sea-level pressure continued to have a general

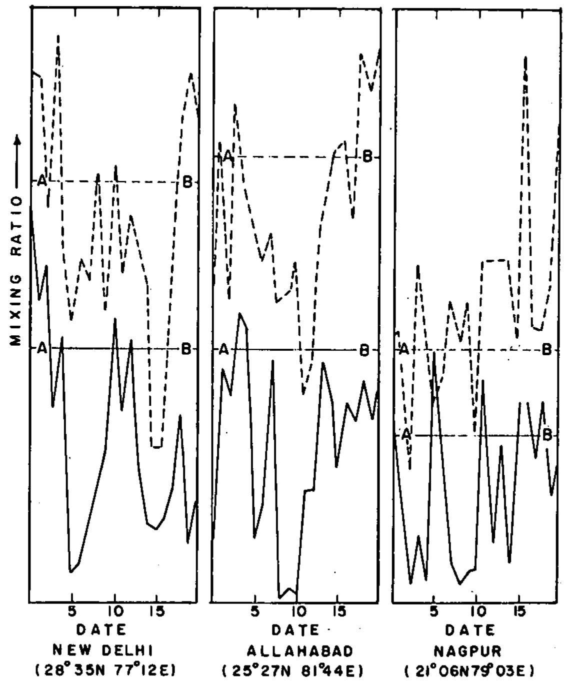

FIGURE 24.—Mixing ratio (g/kg) during August 1965 at 900 mb (dashed line) and 600 mb (solid line). Line AB represents the monthly normal.

TABLE 2.—*Sea-level pressure (mb) at 0300 GMT during August 1965*

Date	Guna (24°39′N, 77°19′E)	Allahabad (25°27′N, 81°44′E)	Pendra (22°46′N, 81°54′E)	Indore (22°43′N, 75°48′E)
1	999. 3	997. 3	999. 8	1001. 5
2	1001. 0	999. 3	1001. 1	1003. 0
3	1002. 9	1001. 3	1003. 4	1005. 5
4	1003. 6	1001. 2	1002. 6	1005. 1
5	1004. 0	1001. 3	1003. 4	1005. 9
6	1004. 0	1001. 3	1003. 6	1005. 6
7	1004. 1	1001. 4	1003. 6	1005. 9
8	1004. 1	1001. 9	1003. 9	1006. 4
9	1003. 8	1003. 0	1004. 2	1006. 5
10	1004. 8	1003. 6	1005. 5	1005. 9

increasing tendency (table 2), even after the monsoon trough reached the Himalaya on the afternoon of August 3.

During the break-monsoon, pressure values from sea level to 100 mb increase, resulting in a ridge of high pressure from sea level to 500 mb over central India. This ridge is most pronounced from 850 to 500 mb. According to Pisharoty and Asnani (1960) and Dixit and Jones (1965), the ridge at 500 mb is capable of inhibiting ascending motion.

During the normal monsoon, the trough of low pressure dominates the troposphere over central India from sea level to 500 mb; above this Low are the subtropical anticyclones, which extend up to 100 mb, with their axes running near the Himalaya. During the break-monsoon, this low-level trough of low pressure is replaced by a ridge of high pressure, and the entire troposphere from sea level to 100 mb is a high-pressure region. As pointed out by Ramaswamy (1962), the upper tropospheric anticyclones

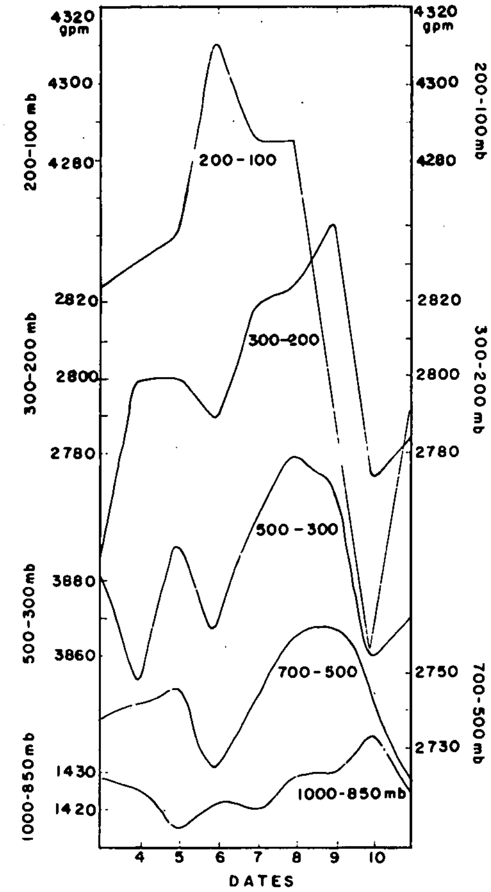

FIGURE 25.—Variation of thickness between different isobaric levels at Nagpur during the break-monsoon of August 1965.

then shift southward over the plains with westerlies reaching as far north as 26°N.

Moreover, as the break-monsoon intensifies, the troposphere as a whole gets warmer, as can be inferred from the vertical stretching of the troposphere (fig. 25). The warming is greater in the upper troposphere than in the lower troposphere since the vertical stretching of the atmosphere increases at higher levels. Apparently, the source of warming is in the upper troposphere and not in the lower troposphere. Warming of the upper troposphere may be due to one of the three causes; namely, latent heat of condensation, horizontal advection of warm air, or subsidence from the stratosphere. Latent heat of condensation can be safely ruled out since there are practically no clouds during the break-monsoon. Examination of the daily variation of upper tropospheric temperature over Southeast Asia shows that there is no horizontal advection of warm air to northern India during the break-monsoon. Figures 26–30 illustrate this, showing the isotherms at 300 mb during the intense break-monsoon of August 1965. Since the warming is not due to latent heat or horizontal advection, we would expect sinking motion from the stratosphere to the troposphere. Computation of vertical motion could confirm this assumption, and it is hoped that satisfactory upper air data may soon become available for this purpose.

For sinking motion to be maintained over such a wide region, there must be areas of significant ascending motion

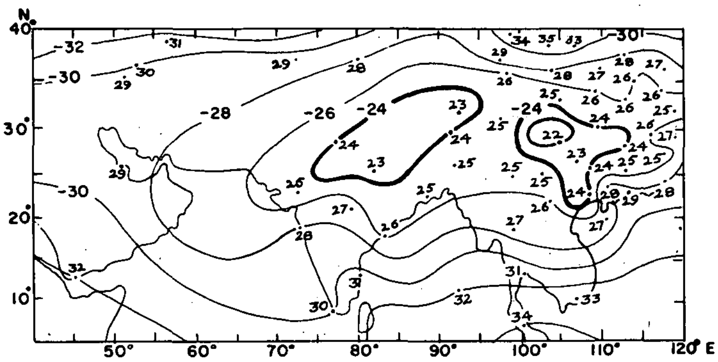

FIGURE 26.—Isotherms (°C) at 300 mb for 0000 GMT, Aug. 2, 1965. Temperature values are negative.

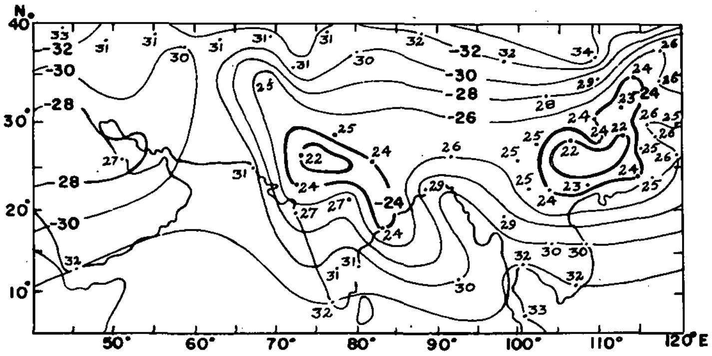

FIGURE 27.—Same as figure 26 for Aug. 4, 1965.

in the general vicinity. Before we look for these areas, we must remember that there are normally two vertical cells over the Indian region (Koteswaram 1960) during the monsoon. One is the Hadley cell, and the other is the anti-Hadley (monsoon) cell (fig. 31A). They have a common ascending limb between 20° and 25°N, the region of high rainfall amounts. There are two descending limbs for these cells, one north of 30°N and the other south of 13°N. During a break-monsoon, there is a radical change in the regime of rainfall, implying a significant variation in the vertical circulation; the principal regions of rainfall are the hills of the Himalaya and the area south of 13°N. Along the hills of the Himalaya, the heavy rainfall and ascending motion may be ascribed to the orography and the monsoon trough. Sea-level pressure is below normal in this region throughout the break-monsoon. Sea-level pressure remains below normal south of 13°N also. Although the genesis of this southern low-pressure area is not fully understood, it is known to frequently deepen, giving rise to heavy rainfall. This deepening coincides with the passage of low-pressure systems that, according to Koteswaram (1950), are generated in the equatorial easterlies of the middle troposphere.

There are, therefore, two major areas of significant ascending motion during break-monsoons, one on either side of central India. The ascending air from these areas can be expected to descend over the adjoining central India. According to our earlier inference, the descending motion may begin in the stratosphere and reach the lower troposphere. The resulting circulation pattern is depicted in figure 31B.

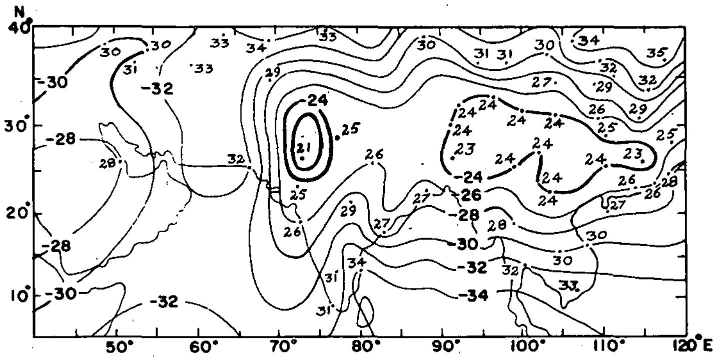

FIGURE 28.—Same as figure 26 for Aug. 6, 1965.

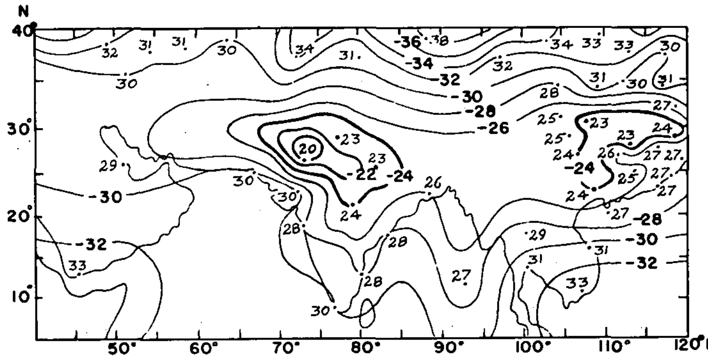

FIGURE 29.—Same as figure 26 for Aug. 8, 1965.

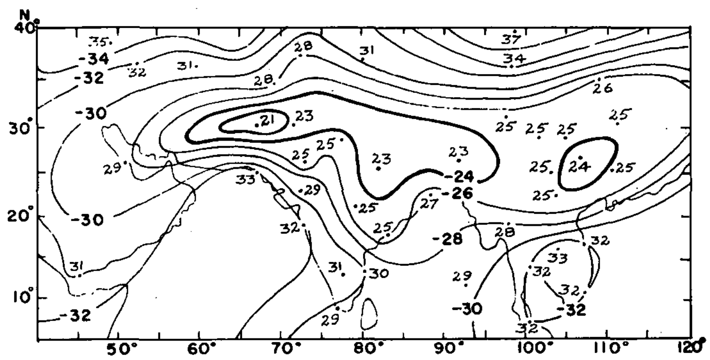

FIGURE 30.—Same as figure 26 for Aug. 9, 1965.

Recall that the transition from a normal monsoon to a break-monsoon is marked by the northward shift of the monsoon trough, which is essentially a manifestation of the ascending limb of the anti-Hadley cell. The anti-Hadley cell of the break-monsoon period is, therefore, the same seasonal one merely displaced to the north; but the Hadley cell in the south seems to be a new development.

These considerations lead us to believe that the convergence in the stratosphere as shown in figure 31B may be a significant contributory factor to the increase of pressure in the troposphere leading to the southward shift of the upper tropospheric anticyclones and development of the high-pressure ridge from sea level to 500 mb over central India during the break-monsoon. During the the break-monsoons of the plains of northern India, there are three high-pressure regions over Southeast Asia, one in central India, another over Iran and adjoining parts of Arabia, and a third over the Pacific Ocean. The high-pressure systems over Iran and the Pacific are intense semipermanent anticyclones, while that over central India is a transient one that develops in situ and

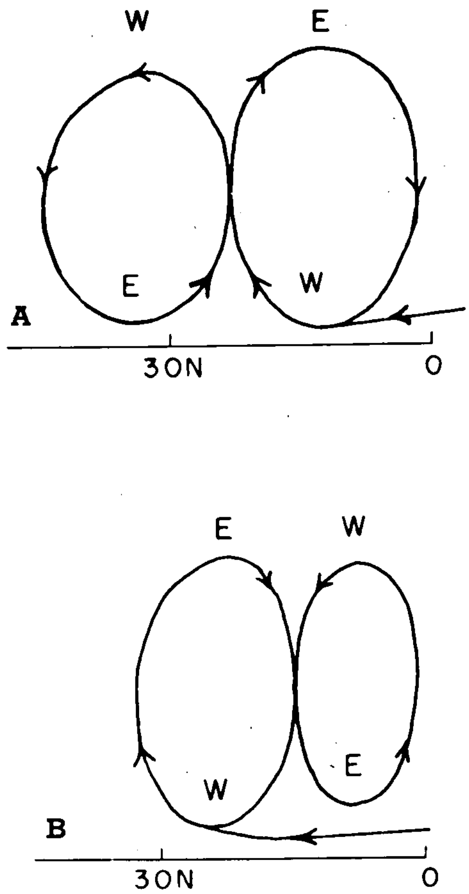

FIGURE 31.—Schematic model of vertical circulation during (A) normal monsoon (Koteswaram 1960) and (B) break-monsoon.

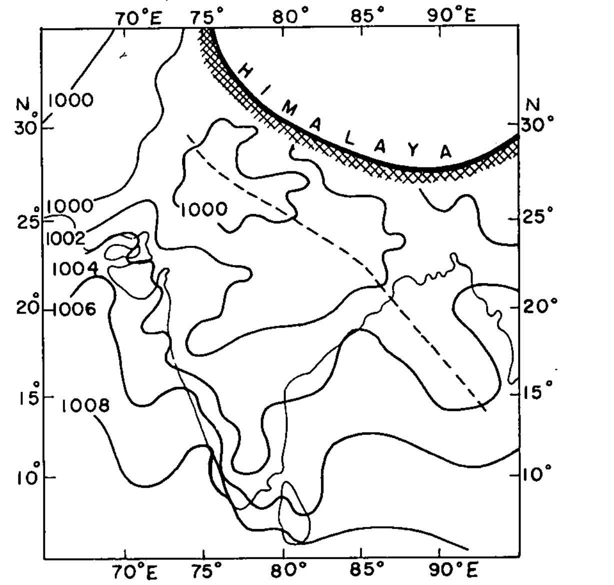

FIGURE 32.—Sea-level isobars (mb) and trough axis for 1200 GMT, Aug. 18, 1965.

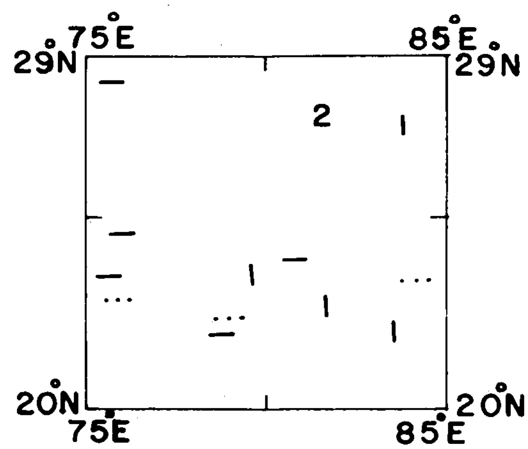

FIGURE 33.—Rainfall (cm) during the 24-hr period ending 0300 GMT, Aug. 19, 1965.

extends only up to the 500-mb level. This weak transient system is generally only a ridge of high pressure and is seldom a closed anticyclonic circulation. Therefore, the high-pressure ridge over central India looks as if it is an extension of the Iran or Pacific anticyclone. Moreover, these anticyclones do not show any noticeable intensification during the periods of break-monsoon.

8. REVIVAL OF NORMAL MONSOON

For the purpose of this study, the normal monsoon is considered reinstated on the day on which at least 75 percent of the stations experience normal rainfall. Revival is generally a slow process, heralded by an increasing number of isolated thundershowers particularly in the southern parts of the plains. Revival of the normal monsoon, however, takes place only after the monsoon trough retreats to the plains. The tropical disturbance has been found to be a factor inevitably associated with this retreat of the trough to the plains. In fact, Rao (1971) showed that these disturbances can result from the barotropic instability brought about by the break-monsoon condition itself. As the tropical disturbance develops at or near the Bay of Bengal (sometimes only in the upper air), the sea-level monsoon trough retreats to the plains with its eastern end approaching the center of the tropical disturbance. As the disturbance moves toward the plains, the monsoon trough intensifies. Widespread typical monsoon rainfall begins as the trough extends upward to at least 700 mb over the plains. A weaker monsoon trough extending to less than this altitude is favorable for widespread afternoon thundershowers.

Figure 32 shows the position of the sea-level monsoon trough on retreat from the foothills of the Himalaya under the influence of a tropical disturbance between 700 and 500 mb in the central Bay of Bengal. The very weak trough did not extend above 850 mb. Although situated well within the plains, the inability of this weak trough to revive the monsoon is evident from the rainfall shown in figure 33.

9. SUMMARY AND REMARKS

Over the plains of northern India, rainfall occurs almost every day on the average during July and August. Ascending motion must be a seasonal feature for this to occur. The terrain over the 300-km belt of the plains adjoining the Himalaya is favorable for the seasonal low-level winds to experience ascending motion. Elsewhere in the plains, the ascending motion can be ascribed to the seasonal trough of low pressure that slopes southward with altitude over the area.

When a tropical disturbance that extends at least from 900 to 700 mb moves in a northerly direction from the plains to the Himalayan region, the axis of the seasonal trough becomes nearly vertical and moves with the tropical disturbance to the Himalaya. When it is at its northernmost position near the Himalayan region, the plains of northern India are deprived of the trough and its associated ascending motion. Moreover, this location of the trough causes the low-level winds over the 300-km belt of the plains adjoining the Himalaya to change direction and become unfavorable for orographic convergence and ascending motion there. Lack of significant ascending motion causes break-monsoon.

As the break-monsoon sets in over the plains, ascending motion and rainfall increase remarkably over the Himalayan region and over the southern parts of India adjoining the Indian Ocean. Orography and the monsoon trough may be mainly responsible for this change over the Himalaya. A separate study will be necessary, however, to understand the changes taking place over southern India. The ascending air from both of these regions appears to reach above 100 mb in the stratosphere and converge, causing descending motion that leads to further decrease of rainfall over the plains. This convergence in the stratosphere may be largely responsible for the development of a ridge of high pressure in the middle and lower troposphere over central India during the break-monsoon.

This ridge is seldom seen as a closed anticyclone. Being situated between the two subtropical anticyclones, one in the west over Iran and Arabia and the other in the east over the Pacific Ocean, the ridge often appears as an extension of these anticyclones. When the ridge intensifies, the quasi-stationary troughs in the middle latitude westerlies near 65°E and 110°E often increase in amplitude. Amplification of the trough near 110°E during the break-monsoon in northern India has been found to influence the weather beyond Japan to about 150°E over the Sea of Okhotsk (Asakura 1968).

The break-monsoon terminates over the plains, and the normal monsoon reestablishes only after the seasonal trough of low pressure retreats to the plains and intensifies. This supports our premise that the absence of the seasonal trough in the plains is the cause for the break-monsoon. The trough retreats to the plains and intensifies when a tropical disturbance develops in the vicinity of the Bay of Bengal and moves toward the plains.

The break-monsoon phenomenon depends, therefore, mainly on tropical disturbances of the Indian region for both its genesis and persistence. The causes of these disturbances and the factors that determine their direction of movement will be subjects of future studies.

This study has not considered short periods (1–2 days) of little or no rainfall even though these situations are often called break-monsoons. Because of their transient nature, however, one may not expect their origin and dynamics to be identical in all respects to those of the persistent ones discussed here.

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REFERENCES

Asakura, Tadashi, "Dynamic Climatology of Atmospheric Circulation Over East Asia Centered in Japan," *Papers in Meteorology and Geophysics*, Vol. 19, No. 1, Tokyo Meteorological Research Institute, Japan, Apr. **1968**, pp. 1–68.

Banerji, S., Rao, D. V. L. N., Julka, M. L., and Anand, C. M., "Some Further Results of Investigations on Quantitative Precipitation Forecasting Over Selected Areas in North India," *Indian Journal of Meteorology and Geophysics*, Vol. 18, No. 4, India Meteorological Department, Delhi, Oct. **1967**, pp. 465–472.

Blanford, Henry Francis, "Rainfall of India," *Memoirs of the India Meteorological Department*, Vol. 3, Part I, Calcutta, India, **1886**, 646 pp.

Dixit, C. M., and Jones, D. R., *A Kinematic and Dynamical Study of Active and Weak Monsoon Conditions Over India During June and July 1964*, Report of the International Meteorological Centre, Bombay, India, Apr. **1965**, 26 pp. and numerous charts.

Frost, R., and Stephenson, P. M., "Mean Streamlines and Isotachs at Standard Pressure Levels Over the Indian and West Pacific Oceans and Adjoining Land Areas," *Geophysical Memoirs* No. 109, Her Majesty's Stationery Office, London, **1965**, pp. 1–24.

Koteswaram, P., "Upper Air 'Lows' in Low Latitudes in the Indian Area During S. W. Monsoon Season and 'Breaks' in the Monsoon," *Indian Journal of Meteorology and Geophysics*, Vol. 1, No. 2, India Meteorological Department, New Delhi, Apr. **1950**, pp. 162–164.

Koteswaram, P., "The Asian Summer Monsoon and the General Circulation Over the Tropics," *Proceedings of the Symposium on Monsoons of the World, New Delhi, India, February 19–21, 1958*, Manager of Publications, New Delhi, **1960**, pp. 105–110.

Krishnamurti, T. N., and Hawkins, R. S., "Mid-Tropospheric Cyclones of the Southwest Monsoon," *Journal of Applied Meteorology*, Vol. 9, No. 3, June **1970**, pp. 442–458.

Murakami, Takio, "Maintenance of the Kinetic Energy of the Disturbances Appearing on the Monthly Mean Weather Charts," *Journal of the Meteorological Society of Japan*, Ser. 2, Vol. 41, No. 1, Tokyo, Feb. **1963**, pp. 15–28.

Normand, C. W. B., *Climatological Atlas for Airmen*, India Meteorological Department, New Delhi, **1943**, pp. 1–100.

Pisharoty, P. R., and Asnani, G. C., "Flow Pattern Over India and Neighbourhood at 500 Mb During the Monsoon," *Proceedings of the Symposium on Monsoons of the World, New Delhi, India, February 19–21, 1958*, Manager of Publications, New Delhi, **1960**, pp. 112–117.

Raman, C. R. V., and Dixit, C. M., "Analyses of Monthly Mean Resultant Winds for Standard Pressure Levels Over the Indian Ocean and Adjoining Continental Areas," *Proceedings of the Symposium on Tropical Meteorology, Rotorua, New Zealand, November 5–13, 1963*, New Zealand Meteorological Service, Wellington, **1964**, pp. 107–118.

Ramaswamy, C., "Breaks in the Indian Summer Monsoon as a Phenomenon of Interaction Between the Easterly and the Subtropical Westerly Jet Streams," *Tellus*, Vol. 14, No. 3, Stockholm, Sweden, Aug. **1962**, pp. 337–349.

Rao, Brahmananda, V., "Dynamic Instability of the Zonal Current During a Break-Monsoon," *Tellus*, Vol. 23, No. 1, Stockholm, Sweden, Jan. **1971**, pp. 111–112.

Thompson, B. W., *The Climate of Africa*, Oxford University Press, New York, N.Y., **1965**, 132 pp. (see pp. 1–15).

Wiin-Nielsen, A., Brown, John A., and Drake, Margaret, "Further Studies of Energy Exchange Between the Zonal Flow and the Eddies," *Tellus*, Vol. 16, No. 2, Stockholm, Sweden, May **1964**, pp. 168–180.

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